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THEORETICAL AND EXPERIMENTAL STUDY
OF IGNITION LAG AND ENGINE KNOCK

By Fritz A. F. Schmidt

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THEORETICAL AND EXPERIMENTAL STUDY OF IGNITION LAG AND ENGINE KNOCK*

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SUMMARY

The author believes, on the basis of experimental ignition-lag data, that the character of a fuel cannot be stated in terms of a single constant (such as octane or cetene number) but that at least two and generally three constants are required.

Thus no correlation between knock ratings can be expected if in one set of tests the charge temperature was varied while in the other the charge pressure was varied.

For this reason, he favors knock rating being based on an equation characterizing the ignition lag of the fuel as a function of pressure and temperature of the charge.

I. INTRODUCTION

The individual processes accompanying the combustion in an engine are so complicated as to make their investigation extremely difficult. However, experiments with engines have made it possible to calculate the total process of combustion and particularly the end of combustion, by determination of the burnt fuel volume in relation to the crank angle. In the attack on this problem, the studies with calorimetric bombs (references 1 to 5) and in pipes (references 6-11, 29, 30) have proved very valuable. For instance, the ignition lag values were also measured

*"Theoretische Untersuchungen und Versuche über Zündverzug und Klopfvorgang." VDI-Forschungsheft 392, Supplement to Forschung auf dem Gebiete des Ingenieurwesens, ed. B, vol. 9, September/October 1938, pp. 1-14.

in this manner. But the manner in which in these tests the chemical change of the fuel molecules with the oxygen takes place, has not been sufficiently explored. The exact calculation of the reaction process has up to the present been successful for very few reactions following a known pattern (for instance, bimolecular reactions, etc.) (reference 12), while the data on the reaction at oxidation of complex compounds are very incomplete (references 6 and 9). Even more difficult is the investigation of commercial fuels incorporated of a large number of complicated blends.

But, for commercial purposes, it is not necessary, in the majority of cases, to know all partial processes; it suffices to determine the regularity of the total process as total result. Engine studies would be much easier if the phenomena observed during combustion could be traced back to a minimum of fundamental laws. The good reproducibility of ignition-lag tests and the fact that the combustion processes reproducible within certain limits can be influenced by physical conditions (for instance, pressure, temperature) seem to indicate that it might be possible to ascertain the processes accompanying combustion accurately enough for engineering purposes by standard methods based on few laws even without knowing the exact mechanism of reaction. Once the fundamental laws are accurately enough available, it should be possible to draw some important conclusions for the improvement in fuel testing and development. For the interpretation of engine tests, it is of particular importance to establish the relationship existing between the physical test of combustion in a pipe, the combustion in the calorimetric bomb (for example, ignition-lag measurements) and the processes accompanying the combustion in Otto and Diesel engines in order to be able to deduce from these physical tests simple relations which can be applied to the complicated engine tests. Then it would be possible to follow the combustion process mathematically under any change in physical assumptions, such as at the different pressure and temperature changes due to piston stroke or the movement of the flame front.

In the following the relations between engine and bomb test data are discussed on the basis of theoretical considerations.

II. IGNITION LAG

1. Generalities

Numerous ignition-lag measurements in engines and calorimetric bombs have proved a definite connection between ignition lag period,* temperature, and pressure (references 13, 2, and 5). Since it was possible to extend the bomb studies over a wide temperature and pressure range the findings are very accurate. But the allocation of ignition lag in the engine to certain temperatures and pressures is uncertain because of the rapid changes in these two quantities. Aside from that, the scope of investigation is very limited on account of the short time available and the thus imposed narrow limit for maximum ignition lag.

The elucidation of the causes of ignition lag in the engine and in the bomb calls for an investigation of the thermal processes involved, i.e., of the processes of heating and vaporization, as well as of the chemical changes, that is, of the reactions.

Theoretical and experimental studies have shown that the thermal processes, especially the heating and vaporization cannot be the sole causes of ignition lag. In support of this, we computed the mean temperature rise and the time rate of vaporization of fuel droplets with due allowance for the variable drop velocity, using Wetzels calculation (reference 14) as basis.

Various simplifying assumptions were necessary among others, constancy of air temperature at spray boundary, equal drop size at spray boundary and in spray core, and a distribution of fuel droplets and of the air in the spray core in correspondence with estimated mean values from engine tests (average $\lambda = 0.4$, air temperature 550°C. , pressure 34 atm.). The quantity of air in the spray zone was averaged, because of the continuous expansion of the spray and hence of the mixture ratio during the ignition-lag period. The study discloses, for the spray core, that the time lapse for equal temperature adjustment, can exceed that at the spray boundary considerably (from 20 to 50 per cent for the temperature range chosen in the example).

Although the simplifying assumptions are not alto-

*The absolute ignition-lag figures for different fuels are markedly at variance.

gether true to fact as the drop size at the edge is smaller than in the core, the sought-for results are nevertheless correct in order of magnitude, and so afford a possible comparison of the conditions in the spray core and at the spray boundary. For average drop distribution according to Sass (reference 15)* about 80 percent of the fuel volume is already vaporized at the spray boundary 5/10 000 second after start of spray (fig. 1).

But the ignition-lag periods of several thousandths of a second and even above 1/100 second (at low temperatures), particularly in bomb experiments, cannot be explained by the vaporization process alone; even during the short ignition-lag period in the engine the greater part of the fuel is vaporized in many cases in the spray start interval, so that no systematic relation can be ascertained between vaporization period and total ignition-lag period. It is therefore proper to divide the total ignition lag into a process due to thermal (heating and vaporization) and a process due to chemical causes (chemical reactions during ignition-lag period). Since both processes overlap to a certain extent, the determination of the total ignition-lag period by addition of the two calculated separately, is not rigorously correct, but nevertheless permissible for first approach.

It may be considered proved that the ignition starts at the spray boundary and at several places (simultaneously in part), hence the ignition does not, according to the Diesel principle start from a single core. The combustion starts simultaneously at many points.

Figure 2 is an enlarged view of fuel spray at 1 atmosphere. The light source was an electric spark affording a period of exposure of 10^{-6} seconds with a luminous intensity of the spark of around 6×10^5 HK. In the low-speed range the photographs of the fuel drops are circles, at higher speed the circles turn into bands if the travel of the drop, during exposure, is considerable in relation to its diameter. High velocity exists in the spray core, especially in proximity of the nozzle-exit orifice, whence the fuel drops form long streaks. At the spray border the velocity of the drop slows up consistently, hence the drops appear almost as circles. At the spray tip a large volume of fuel accumulates as a result of the retarding effect of

*Jung's more recent tests (optic observation of droplets in spray) in the DVL give similar results.

the air. From the process, figures 2 and 3, it may be inferred that the drops with low speed at the spray boundary are enveloped by fairly large air masses and are heated quickly, hence ignite first. This is also in accord with the optical observations and the findings from studies by the ionization method into the start of ignition. The comparatively larger fuel masses moved forward in the spray tip do not heat as readily because of the comparatively small air volume available for heating. Stroboscopic records also reveal the spray tip as being continuously fed from within, whereas drop masses at the sides remain behind, so that the spray tip must always be colder than the spray envelope. The drops farther away from the spray become heated and vaporized and readied for igniting.

The calorimetric bomb ignition lag tests were mostly extended into the range of very low temperatures (up to about 350° C.). In this zone a very pronounced temperature relation was ascertained, which earlier experimenters expressed empirically with a function $e^{b/T}$. This relationship is, as demonstrated by the subsequent considerations, evidently largely attributable to chemical causes.

2. Theoretical Studies

For the purpose of explanation of the fundamental influences so far as they relate to the chemical proportion of the ignition lag, the ignition-lag period will be computed for the simple case of reaction between two gases, the assumption being a slow reaction at start but subsequently accelerated as a result of the temperature rise. The period of ignition lag is defined as the interval up to reaching the temperature T_z . (The exact determination of T_z is usually of secondary influence on the result of the calculation, as the temperature rise at the end of the ignition lag is extremely rapid.) These premises were chosen in order to obtain an agreement with the findings from ignition-lag experiments. The first flash of light is generally accepted as characteristic sign for the start of ignition.* The chosen definition

*This assumption is arbitrary, since a combustion is under way even before the appearance of the visible light. Similarly in flame photographs the so-called "flame front" is not the border of the combustion start, since combustion prevails in front of it in the part of the unburnt mixture not illuminated as well as behind in the illuminated part, as a result of which the flame front actually has some thickness. A. M. Rothrock and R. C. Spencer (reference 30) have shown that there is a certain late burning even behind the flame front.

can, moreover, be readily reconciled with other test methods, since the ignition lag whether obtained by ionization method, by optical method, or as determined from the pressure rise, is of the same order of magnitude (reference 16). The definition of ignition lag by reaching a combustion velocity which is determined for a preponderance of heat released by combustion relative to that dissipated by the exhaust, favors the results only in the proximity of the ignition limits. If the temperatures are far above these limits, as, for instance, for ignition in the engine, the heat removal is of secondary importance.

Based upon the above definition, the ignition lag can be theoretically computed for simple cases (reference 32). The calculation is fairly simple for standard gases with known reaction mechanism. For illustration, the derivation for a bimolecular reaction at which no chain reactions take place is given:

Compute the time interval following from the integration of the time elements dz for the combustion process in the whole temperature range from start of reaction to temperature T_z .

Allowing for the impact figure of the molecules and assuming that a reaction between two molecules can take place only when its total amount exceeds a certain value Q_a , the fuel volume $d[B]/dz$ converted in unit time follows, at:

$$\frac{d[B]}{dz} = \pi(r_1 + r_2)^2 \sqrt{\bar{w}_1^2 + \bar{w}_2^2} N_L [O_2] [B] e^{-Q_a/RT} \quad (1)$$

where $e^{-Q_a/RT}$ is the proportion of the successful shocks.

In this formula

r_1, r_2 indicate the mean radii of the reacting molecules

*The processes accompanying the activation are not definitely known; not every shock of activated molecules must of necessity lead to reaction. However, the details and limitations are without the scope of this report.

\bar{w}_1, \bar{w}_2 , the roots from the mean velocity square of the oxygen and fuel molecules

N_L , the Loschmidt number

$[O_2]$, the molecular concentration of oxygen

$[B]$, the molecular concentration of fuel

R , the gas constant

T , absolute temperature

According to Maxwell's law of velocity distribution the proportion of the molecules whose energy exceeds a certain amount E corresponds to an exponential function $e^{-E/RT}$. The frequency of reaction on collision of two molecules is contingent on the probability that the sum of the energies of the two molecules exceeds a certain minimum value Q_a . And this relation holds not only for the kinetic energy of translation but for other forms of energy as well (such as oscillation, rotation, for instance), hence can be introduced generally. The above relation is further supported by test data, since the value $e^{-Q_a/RT}$ can also be obtained empirically.

The heat of activation Q_a could be successfully defined in several reactions from the absolute quantity converted in unit time at a certain temperature, as well as from the change of conversion velocity with temperature (empirical formula by Arrhenius). Hereby, the value Q_a was found to be little affected by temperature, whence it is permissible to consider this value constant in a limited temperature range. The exponential function indicates an extremely great rise in reaction velocity with temperature, so that for the whole duration of a reaction the part at start and at lower temperature, respectively, is largely decisive. The lower the value of Q_a , the smaller is the effect of temperature on the rate of temperature rise.

From the equation of the reaction velocity (equation (1)), the duration for the ignition lag can be obtained by integration in the range between initial temperature and temperature T_z . It gives:

$$Z = \int_{T_1}^{T_z} \frac{e^{Q_a/RT} d[B]}{\pi(r_1 + r_2)^2 \sqrt{\bar{w}_1^2 + \bar{w}_2^2} N_L [O_2] [B]}$$

the differential of the converted fuel volume is substituted by a function of T . It gives:

$$d[B] = \frac{\sum [] M c_p dT}{H_u} \quad (2)$$

where the summation extends over all interested gases corresponding to their molality at the particular temperature (H_u = heat value of fuel, $[] M c_p$ = molality \times molal heat).

Introducing the initial concentration and replacing it with the aid of the combustion equation by a function of the specific heats, the heat value and the maximum temperature rise at complete combustion of the total fuel ($T_{\max} - T_1$):

$$[B]_1 = \frac{(T_{\max} - T_1) \sum []^{T_{\max}} m c_p m \Big|_{T_1}^{T_{\max}}}{H_u}$$

we find, after several changes:

$$Z = \frac{T_1}{p_1} \left(\frac{1}{T_{\max} - T_1} \right)^c \int_{T_1}^{T_z} \frac{e^{Q_a/RT}}{\sqrt{T}} \frac{[O_2] [B]_1}{[O_2] [B]} \frac{\sum []^T}{\sum []^{T_{\max}}} dT \quad (3)$$

where:

$$c = \frac{p_o M c_{p1}}{T_o M c_{p m} \Big|_{T_1}^{T_{\max}} \sqrt{3 R g \left(\frac{1}{M_1} + \frac{1}{M_2} \right) \pi (r_1 + r_2)^2 N_L [O_2]_o}} \quad (4)$$

(p is pressure, T_{\max} , maximum temperature of combustion at constant pressure, computed for the heat value of the

total fuel; M_1, M_2 , molecular weights; g , acceleration of gravity; index 0, the normal state (for instance, 15° C. and 1 atm. abs.), index 1, the initial state of the reaction).

The variation of the specific heats within the temperature range of the integration being small, the specific heats c_p are expressed as constant. The effect of the counter reaction is not perceptible, since the range for which the ignition lag is computed is remote from the equilibrium condition.

The molal concentrations in equation (3) are dependent on the time and temperature, respectively. But their variations during ignition lag is usually little, so that for practical purposes the concentration is considered constant and equated to the initial concentration. In cases where this is not permissible, progressive integration must be resorted to.

For practical application a presentation of the ignition-lag period in function of the initial state is informative. It gives:

$$z = \frac{e^{-Q_a/RT_1} \sqrt{T_1}}{P_1} a \beta \quad (5)$$

The integration constant can be disregarded since the limit value of the ignition lag is very small for high temperatures. The value $\beta = c/g$ (fig. 4) allows for the reduced lag period resulting from the increased rate of burning during the ignition lag period which is due to the temperature rise within this interval. It can be determined from the relation

$$\beta = \frac{e^{-Q_a/RT_1} \sqrt{T_1}}{(T_z - T_1)} \int_{T_1}^{T_z} \frac{e^{Q_a/RT}}{\sqrt{T}} dT \quad (6)$$

where through substitution and partial integration the integral may be reduced to the integral

$$\int_0^x \frac{e^{-x}}{x} dx \text{ available in tables. The change in } \beta \text{ with}$$

the temperature is illustrated in figure 5. Value a is numerically computable; it is little affected by the excess air figure λ (approximately corresponding to $T_{\max} - T_1$, since $T_{\max} - T_1$ is dependent on λ). An increasing λ results in a decrease of a .*

For states of equal, great ignition lag, it is:**

$$\ln p_1 = \frac{Q_a}{R T_1} + \frac{1}{2} \ln T_1 + \ln \beta + \text{const}$$

While the heat removal during the ignition processes in an engine plays a comparatively small part, it is of decisive importance for the determination of the autoignition temperature and must therefore be accounted for since the lowest limit of autoignition is conditioned by the excess of developed, relative to evacuated, heat.

3. Physical and Chemical Processes during Autoignition

The foregoing deductions are for the present applicable only to the simplified assumptions, to which the mechanism of reaction of only a few reactions corresponds. In point of fact the majority of reactions pass through intermediate stages, so that various reactions become superposed, which in many cases are preceded by cleavage processes. Then, too, it must be assumed that the combustion process in nearly all technical cases is by way of chain reaction.

Since at combustion in a Diesel engine and in similar bomb tests with liquid fuel injection, the ignition takes place in small zones of the spray boundary which are no longer affected by the wall, there is no wall effect. Hence arguments and deductions based on chain interruption at the wall are ruled out. The reaction mechanism of commercial fuels is surprisingly little known; even for elementary substances such as methane the course of combustion

*For empirical presentation of test curves on ignition-lag values, a , β , \sqrt{T} , may be considered constant. In this case a somewhat higher mean temperature takes the place of T_1 .

**Other investigations into the relationship existing between the minimum pressure and temperature at which autoignition occurs known from literature have resulted in a similar formula but with different constants.

is so complicated that no definite explanation has ever been published. It is known, for instance, that the methane combustion is over methanol and formaldehyde. CC and CH bands were also observed. The intermediate products continue, in part, to disintegrate under heat. The products obtained on the basis of such observations correspond to several intermediate reaction stages, so that for the final termination of the reaction process several shocks are required. Even for the chain reactions the conversion processes are still not accurately known, hence a purely theoretical derivation of the ignition lag is for the present impossible for these substances.

From the reproducibility and uniformity of the regularities of the test data for changing pressure and temperature it can be concluded that the frequency of reaction start is so great that the disparity of the individual processes during the course of reaction does no longer appear in the measurement of the total process.

The assumption also suggests itself that the chain reactions produced by the first reaction of fuel molecules are numerous enough to justify their expression by a mean reaction. Besides, the observations of the processes accompanying ignition at the fuel spray lead to the concept that the reaction starts at a particularly propitious point, favored on the one hand by conditions conducive to heating of the droplets, i.e., high temperatures, and on the other, by the presence of optimum mixture ratio. Since ample reaction or molecular shock* frequencies are possible even in a very small space compared to the fuel spray, it may be assumed that in every fuel spray the optimum mixture ratio exists at several points. The reproducibility of the experiments vouches for the fact that in tests under identical initial conditions the assumptions for the creation

*The order of magnitude of the shock frequencies is apparent, for instance, from the fact that at a pressure of 30 atm. and a temperature of 500° C. the shock figure of a molecule already amounts to about 10^{11} per sec., with the order of magnitude of the radius of the molecule at 10^{-8} cm. In 1 mm^3 the number of molecules would amount to $\approx 10^{17}$. Considering a bimolecular reaction with an activation heat of $Q_a = 8,000 \text{ R}$, it gives at 500° C. - corresponding to the factor $e^{-8000/T}$ a successful shock each 30,000 impacts. The change in the number of reactive molecules with the temperature is considerable by reason of the dependence on function e . For the same example every 3,600 shock would be successful at 700° C.

of the optimum mixture ratio are essentially the same - even though temporarily at different points.

Despite the fact that an exact calculation of the combustion processes is impossible, the above considerations make it appear feasible that the chemical share on ignition lag for chain reaction and for nonstandardized fuels (gasoline, for instance) can be reproduced by a formula similar to the one developed here. Because of the existing intermediate reaction the pressure appears as power with an exponent n . Although the reaction mechanism for the processes leading to autoignition during the ignition-lag period are not known individually, it is possible to establish, on the basis of the deduction from the formula for the chemical share of the ignition lag, a reaction formula with the aid of the measured regularities which would afford the same result for the relations of the chemical ignition-lag share as the measurement.

From the formula*

$$z = \frac{e^{b/T} \sqrt{T}}{p^n} a \beta \quad (5a)$$

for the chemical ignition-lag quota, we obtain in correspondence with the foregoing derivation for the reaction equation, the expression

$$\frac{d[B]}{dz} = \frac{p^n d}{e^{b/T} \sqrt{T}} \quad (8)$$

where d indicates another constant obtainable approximately from the measured ignition-lag values by approximate consideration of the thermic ignition-lag share.

Equation (5a) takes account of a temperature rise during the reaction. In chain reactions the possibility exists - in principle - that the reaction is very rapidly accelerated without appreciable temperature rise. (See

* Value b substitutes for value Q_a/R , since the physical interpretation of the heat of the activation does no longer apply here.

Semenoff theories.) The purely isothermic reaction of fuels, which, on the whole, burn with considerable heat development, can, however, be only considered as a special case. The assumption that heat is released even during chain reaction as a result of the formation of the end products, is the more general.

The three constants b , n , and d , in equation (8) should be obtained from the ignition-lag tests by means of equation (5a). They present in this case no physically accurately defined quantities, but averages to be interpreted as empirical quantities. Obviously the correct definition of the constants in this equation requires the selection of the accurate equation of the chemical ignition-lag quota as a basis, wherein the value β is accounted for conformably to equation (6), or else a wrong value b is obtained. When computing β , the value b substitutes for $\frac{Q_a}{R}$ in equation (6). An equation expressing the process during time interval dz can be formulated from the recorded ignition-lag values only with allowance for the temperature variation during ignition lag, represented here by the value β . The change of β with the temperature (fig. 5) is hereby not as important as the allowance for the absolute value of β , which is followed by a substantial reduction of the exponent in the value $e^{b/T}$, when b is empirically obtained from experiments. The thus obtained relation is then applicable to other ignition processes with any other pressure and temperature change. The constants, of course, must be interpreted empirically, but the derivation affords a basis of their significance.

The empirically defined reaction velocity (equation (8)) computed in this manner from the ignition lag is a little too low because in the derivation of formula (5) for the chemical ignition-lag share it was assumed that the fuel vapor-air mixture manifests the temperature of air at the point where the reaction sets in. In reality a certain cooling of the air has taken place at the points where the fuel concentration reaches higher values as a result of the heating and vaporization. Hence the computed reaction velocities according to equation (8) are actually reached at slightly lower temperatures than assumed in the calculation.

Since it concerns an empirical formula that charac-

terizes the whole process, the manner in which the reaction actually proceeds (intermediate, chain reaction) is immaterial. This assumption is borne out by the fact that even cases with proved intermediate reaction (for instance, in CH_4 combustion) manifest relations which can be reproduced by formula (5a) within the limits of instrumental error. In many cases the character of the reaction itself changes in higher temperature ranges so that quantity b also remains constant for limited temperature range only. It is perfectly conceivable that for very short ignition-lag periods and large droplets a nonuniform reaction in the boundary layer of the drops is involved, which as partial reaction and in certain zones could equally appear as predominating reaction. The sudden inflammation observed in ignition-lag tests is, according to the foregoing theory, explainable as a rapid temperature rise at the end of the ignition-lag period. The temperature rise at the end of ignition lag, which follows

with the function $\frac{e^{b/T\sqrt{T}}}{p^n d}$ (equation (8)), when employing

the conventional calculation of the combustion temperature, is so steep when based on the constants b and n obtainable from ignition-lag data for commercial fuels, that the impression of a sudden ignition can well be gained. The temperature used as basis for the definition of ignition lag as end state, plays here a lesser part. According to figure 6a, the temperature rise in the range between 1,300 and 17,000° K. is already so steep for $b = 8,700$ that practically the same ignition-lag period would have to be assumed for both terminal temperatures. The temperature rise based upon the value $b = 23,000$ (fig. 6b) is even steeper. This value is in order of magnitude similar to the exponent involved in methane. The abscissas in figure 6 are proportional to the time. (See also equations (5) and (6)).

4. Comparison of Theoretical and Experimental Results

The foregoing ignition-lag formula holds for the chemical share only. But, if the heating and vaporization processes play a secondary part compared to the chemical changes a comparison of the formula with the measured ignition-lag values is appropriate in first approximation. Should this comparison disclose a good agreement between test data and formula, it still would afford no proof that in this case the effect of the thermal processes on the

ignition-lag period is small, but merely show the possibility for it. The basic principles for the determination of the thermal effects on ignition lag are, however, so little understood that an inclusion in the interpretation would be premature. For the present, the comparison of the test data with a law which, in development of its formula, corresponds to that for the chemical ignition-lag share is of interest.

The evaluation of ignition-lag tests reveals the test values to be very closely represented by the chemical-share formula:

$$z = \frac{e^{b/T} \sqrt{T}}{p^n} a \beta \quad (5a)$$

The test data can also be represented in simplified form

$$z = \frac{e^{b'/T} \sqrt{T}}{p^n} a' \quad (9)$$

or

$$z = \frac{e^{b''/T}}{p^n} a'' \quad (10)$$

since the variation of β can be equalized by a change in the value b (then expressed with b' or b''); a' and a'' are then new constants also, which account for the omissions in equations (9) and (10) relative to equation (5a). Figure 7 shows the same ignition-lag test data by Lindner (reference 13) compared with the three formulas (5a), (9), and (10). It is apparent that the effect of the e function is so predominating that the lesser change of \sqrt{T} and β is not important.

The possibility of expressing the ignition-lag test data by formula similar to the empirical (10) has been voiced by various research workers on the basis of studies with methane. The accord of this formula with the test data is better for gases than for liquid fuels, because the thermal share of gases is little or not at all apparent. In the high-temperature range particularly the effect of the thermal share in liquid fuels is pronounced, because of the marked drop in the chemical share with the temperature in conformity with the e function. However, there may be cases where, in the low temperature range, the time lapse for the thermic processes is considerably

greater. And agreement of test data and formula itself is no proof of the predominating effect of the chemical share. Hence, the evaluation of ignition lag test data of liquid fuels must allow for the thermic share also.

It is not yet clear whether it is permissible to equate the total ignition lag in first approximation to the sum of the two shares. The division of the total lag in chemical and thermal share empirically is extremely difficult. An approximate division was possible on the basis of the mathematical determination of the thermal share and on the basis of comparisons of fuel tests of widely varying volatility under otherwise identical conditions. The correctness of such a division can be effected on the basis of comparative tests of fuels with and without preheating and on the basis of a separate experimental study of the processes during heating of the fuel droplets. Comparative ignition tests with the gaseous and liquid phase of the same fuel under way at present are hoped to provide further information on this subject.

Apart from the experiments illustrated in figure 7, numerous tests of other research workers (Holfelder reference 2, fig. 8, and Wolfer*) have equally produced results which are reproducible by the above formulas. More recent tests by Professor Nagel with the improved Holfelder equipment have disclosed a smaller pressure relation for ignition lag. In most cases value b may be figured constant for the whole explored range; only in very few cases are appreciable differences noted** in the exponent of $e^{-b/T}$ at different temperatures. Even bimolecular reactions manifested in isolated cases different activation heat Q_a in different temperate zones (reference 12), whence it is very likely that even in complex combinations similar changes in reaction with temperature are involved.

The fundamental similarity of the experimentally and theoretically defined laws for ignition lag constitutes a proof for the assumption that the cause of ignition lag, apart from the thermal processes, is essentially attributable to a reaction or combustion combined with heat,

*Wolfer's tests are described in the present article.

**Thus, for instance, some organic combinations manifest two different oxidation mechanisms in individual temperature ranges (reference 17 and 18).

which ignites first at the points of most propitious conditions for temperature and mixture ratio. A relationship of the ignition lag in a Diesel engine on excess air is therefore not involved, because ignition always starts at the point of most favorable excess air. (For the cooling effect of vaporization, significant with little excess air, see under sec. 5.)

On the other hand, the shortest ignition lag within range of the fuel spray occurs at the point where the necessary mixture ratio and the maximum temperature meet. In well developed fuel sprays the droplets at the edge are less dense and the cooling effect of vaporization is less apparent.

5. Effect of Ignition Lag on the Behavior of the Engine Especially at Altitude

The ignition-lag periods measured in engine tests usually made at the same pressure and temperature are in general smaller than in calorimetric bombs. The reason for this was commonly ascribed to the varying degrees of turbulence. But there can be no substantial turbulence effect unless the air motion produces more favorable heating conditions for the ignitable fuel particles. Small, (reference 3) in his bomb tests with and without turbulence could detect no measurable difference in ignition lag. Hence it is to be assumed that the turbulence has in general no essential effect on the ignition lag, even though the conclusion suggests itself on the basis of various other investigations that recorded differences might be traceable to turbulence. Greater ignition lags have been recorded on numerous occasions with low-speed engines referred to equal pressure and temperature, but these are caused partly by lower compression. Any decision of the extent of this phenomenon attributable to turbulence is difficult in engine tests. There is a possibility that hot spots in the engine cylinder might affect the ignition lag considerably.

The engine operating cycle has very little effect on ignition lag (fig. 9). Engines operating on different principles have disclosed little difference in absolute values and little difference in temperature effects. Similar agreement prevails for the relation of ignition lag to specific weight (fig. 9) and temperature (fig. 10).

The curves refer to identical fuels and optimum engine adjustment (appropriate nozzles). The temperature effect becomes so much less as the temperature is higher and becomes practically insignificant at around 700°C . The pressure effect is more noticeable for low than for high specific weight.

In the presentation of the ignition lag values recorded in the engine, it is to be noted that different lag periods can occur at the same compression if the spray period is changed. The magnitude of the ignition lag depends upon the amount of heating by the temperature of the air, which in an engine varies during the compression cycle approximately according to a sinusoidal function with the time. Hence, the more the ignition-lag periods approach the apex of this sinusoidal line the shorter the recorded-lag period will be. The differences due to change in spray periods are shown in two curves in figure 10.

The recorded pressure relation is, in order of magnitude, in close agreement with the theoretical. It should be borne in mind that the rate of vaporization rises only with one power of the pressure whose exponent is less than one.

With the ignition lag, the engine performance itself is dependent on altitude. Therefore, engines with high compression and consequently small ignition lag have a smaller power drop with altitude than those with low compression (fig. 11).

The experiences with pressure and temperature in their relation to ignition lag are of particular importance for the control of the operating cycle and for the power computations of Diesel engines at altitude.

The power drop of the Diesel engine in relation to altitude is, according to past test data, unlike that of the Otto engine (fig. 11). At low heights - up to around 2 kilometers (6,500 feet) - a smaller power reduction is obtainable with a Diesel engine, because the excess air permissible at sea level for cruising load can be lowered with the usual control for increasing height without increasing the thermal stresses of the engine over those at sea level. At greater heights, of course, the output of a Diesel engine drops in general more than in an Otto engine and principally because of the rise in ignition lag as a

result of lower pressure and low temperature at terminal compression.

According to the pressure-time card (fig. 12), the ignition starts later with increasing height, thus vitiating the performance and raising the fuel consumption. This phenomenon is particularly vitiating in engines with divided combustion chamber, where, as a result of the lowered air density, the ignition in the chamber occurs so late that conditions in the main chamber are as a result of the already lowered pressure unfavorable for the subsequent combustion. In air-cell engines only a relatively small quantity of air (excess air factor very small) is available in the cell. Because at low air density and low air temperature (at altitude) the ignition-lag periods are long, more fuel can vaporize during this lag period. Owing to the small amount of air available, a marked cooling takes place through which in certain circumstances the ignition may stop altogether.

But with smaller ignition lag under normal operating conditions, the ignition already starts at the spray edge while fluid fuel is still present in the spray core, so that the cooling at the points of ignition as well as on the whole becomes less. In altitude tests with a Lanova engine (its principle is described in reference 19) the ignition stopped quite abruptly at lowered excess air, as became manifest for instance at an induction pressure equivalent to an altitude of about 13,125 feet and without changed spray timing ($\epsilon = 12.5$) with an excess of air of $\lambda < 1.2$; at higher compression ($\epsilon = 15$) the ignition missed only after reaching an induction pressure equivalent to 19,685 feet and $\lambda < 0.85$. A check of a vaporization test carried out on the basis of Wentzel's calculation (reference 14) disclosed that at 80 percent vaporization of fuel the air temperature in the cell would have to drop to 270° C. As at this low temperature ignition can no longer take place within the time interval required at 1,500 r.p.m., it follows that a large portion of the fuel is expelled in nonvaporized state from the cell.

The behavior at altitude of a Diesel engine can generally be improved by raising the compression, which affords a higher temperature of compression and a high pressure of compression and consequently a smaller ignition lag, or by adaptation of the penetration of the fuel spray to the low density of the charging air and by earlier ignition at increasing height. Figure 13 illustrates pressure-time rec-

ords with higher compression ($\epsilon = 15$) for different heights than shown in figure 12.

But along with the undesirable effect of the too-long ignition lag, the extremely short lag is equally as undesirable in most cases. Only limited air velocities are available for carburetion, hence a minimum time interval is necessary prior to start of ignition and during incipient combustion in order to assure the distribution of the fuel in the cylinder. If the ignition starts too soon this process of carburetion is often considerably disturbed.

III. DETONATION

1. Physical and Chemical Phenomena

Accompanying Engine Knock

Investigations into the detonation characteristics of engines, especially into the knock limitations under varied operating conditions have led to the conclusion that the detonation process can be definitely influenced by the pressure and temperature of the inducted air (reference 33). The observations point to a reaction in the unburnt portion of the gas mixture compressed by the advance of the flame front as the principal cause of the detonation rather than vibration phenomena. According to the findings of the experiments related hereinafter, the process of combustion and the creation of detonation is - with due regard to the previously held views, especially by Ricardo (reference 20) wherein detonation is attributable to a sudden combustion of the unburnt portion of the mixture - approximately as follows:

While the combustion front, starting at the spark plug, advances at a speed dependent on the turbulence, excess of air, pressure and temperature of the mixture, there is a slow reaction or burning in the unburnt portion at about the same rate as applies to the chemical proportion of the ignition lag in Diesel engines. The rate of this reaction is governed by the pressure and temperature of the unburnt portion. This temperature increases as a result of the displacement effect of the burning part even after dead center. With high compression (for instance, $\epsilon = 8$) and at 80° charging air temperature the temperatures of the unburnt part rise in the range between 20° crank

angle B.T.C. and 10° A.T.C. from around around 450° to 650° C. The slow combustion process is followed by a continuous temperature rise in the unburnt part, which in turn speeds up the rate of combustion so that, according to equation (8) and the measured values spontaneous ignition is to be expected in the unburnt mixture soon after T.C.

A rough check of the experimental data itself indicates that the terminal temperature of the unburnt part due to compression at the instant of incipient knock cannot be considered as the sole cause of detonation, but that the concept of a supplementary slow reaction is in better agreement with the experimental data. (This is also in accord with the measurements by Withrow and Boyd (reference 29), who observed the slowing up of the flame front prior to detonation, in contrast to Rothrock and Spencer (reference 30), who observed this slowing up of the flame front only in several cases). As to the course of this reaction, it was definitely established that the temperature and furthermore the pressure of the unburnt part are of primary significance.

2. Experimental Results and Theoretical Interpretation of Detonation Tests

The available methods of objective measurement of the detonation are as yet quite inaccurate. The measurements are chiefly based upon measuring the rate of pressure rise or on optical observation of the flame front during combustion. A much simpler, but more unreliable method, is afforded by the observation of the detonation noise.

For the exploration of the detonation process either the individual process in the cylinder - especially through measurement of the processes in the flame front and in the unburnt mixture portion - is studied or else the knock limitations under varying test conditions are chosen as a basis. Both methods are of equal promise.

In the following, it is attempted to trace the detonation by the method of changing knock limitations.

Figure 14 illustrates the knock limitations with changing the spark advance. In order not to exceed these limitations, the pressure in the inlet pipe was lowered at

greater spark advance. The changed limit and the compression ratio ϵ along with the correlated mean pressures p_e are shown in figure 15. The accuracy of the obtained limitation through audition is seen from the scattering of the test points.

The test results permit the conclusion that the reaction processes in the unburnt mixture are the primary cause of detonation, and the pressure waves secondary. Pressure waves accelerate the internal reaction up to ignition in the mixture already close to the ignition boundary. If the temperature and pressure rise, due to an existing pressure wave, suffices during the interval of passage of the wave to heat the mixture, already close to spontaneous ignition as a result of the pre-reaction, to visible ignition, the flame front can pass through the space still replete with unburnt mixture at sonic velocity.

In order to check these concepts and assumptions, the detonation experiments were evaluated on the assumption that the reaction presumed to be the chief cause of detonation follows the same laws as the reactions causing the spontaneous ignition in ignition lag. Hence the equation,

$$\frac{d[B]}{dz} = \frac{p^n}{e^{b/T} \sqrt{T}} \quad (8)$$

which, at constant excess of air, gives the correct presentation of the relation between the ignition lag of gases on pressure and temperature with the constants to be defined from the measurement, as derived from the results concerning the dependence of the chemical proportion of the ignition lag on pressure and temperature. In this attempted evaluation of the detonation tests the reaction in the unburnt part which leads to detonation is assumed to be constant. But various investigations have shown the reaction in such gasoline mixtures to be extremely varying at different temperature ranges. It is perfectly possible that similar phenomena take place in detonation. When, in spite of it, it was possible on the basis of such an evaluation to reach the conclusion that a uniform reaction is feasible, it still does not prove it, because such agreement can also be obtained if in one certain range a predominating reaction takes place with such laws.

In the evaluation, the pressure and temperature of the unburnt mixture at adiabatic compression were determined from the indicator cards in relation to crank angle. With the aid of the thus obtained temperature curve, a new temperature curve for the unburnt portion was established by progressive integration on the basis of the above formula. In this new curve, the temperature rise due to advancing flame front and to the internal combustion was allowed for.

If the detonation is to be explained by a reaction in the present form, a portion of the mixture must still be unburnt (reference 21) at the moment when the reaction velocity and the temperature rise become very rapid. In experiments based upon knock limitations, the flame front must at this instant have advanced far enough so that a small portion of the mixture in the cylinder still remains unburnt. Since unburnt parts are equally existent behind the illuminating flame front, it is possible under certain circumstances that detonation occurs even in cases where the flame front has almost traversed the combustion chamber (reference 30). For that reason, an exact evaluation of the experiments by this method necessitates an exact record of the time interval and crank angle, respectively, at which detonation starts, and the movement of the flame front itself must be known.

The time interval of incipient detonation was checked by quartz indicator and the evaluation of the combustion process was accomplished by stroboscopic record of the indicator card and glow lamp indicator. The combustion process was determined from the energy balance for the combustion and expansion cycle (reference 22). (See also combustion studies by Drinkwater and Egerton (reference 23). The result is illustrated in figure 16. Here the flame front has reached the end of the cylinder at about 20° A.T.C., i.e., the combustion for this time interval has ended.*

*This method of determining the combustion process is in close accord with direct measurements of flame fronts in the cylinder. The paths of the flame fronts as measured by Bouchard, C. Fayette Taylor, and E. S. Taylor, correspond to a similar transformation of the fuel quantities, as established in the present experiments. Rassweiler and Withrow (reference 26) measurements also agree with the present evolutions. The direct measurements of the path of the flame front merit preference over the theoretical determination carried out here. (For flame-front measurements, see also F. Kneule (reference 27)).

Measurable or auditive detonation could occur only if the detonation in the unburnt part occurs at the latest in the range between 5° and 15° crank angle. The combustion process shown varies considerably, however, with the operating condition. When evaluating a large number of indicator cards, it was found that the crank angle, at which combustion is terminated, and the entire combustion process is first of all dependent upon the ignition period and shifts almost like the ignition, that is, retarding the ignition 10° is followed by a delay of about 10° in combustion. In several cases it was also observed that the difference of the crank angles in the combustion process was a little less than the spacing of the spark timing. The r.p.m. is of little influence. This result agrees with the fact that the increase in ignition speed is almost proportional to the r.p.m. and approximately proportional to the speed of turbulence. The combustion process in relation to crank angle is little influenced by changing compression, air temperature, or charge pressure, while a change in excess of air works profound changes in combustion (reference 30, also 31). In other words, all influences affecting the rate of ignition, influence the combustion process. Hence the marked difference in time interval or crank angle involving the detonation with changed excess of air and spark advance (reference 30) and the minor difference in changes in initial temperature and pressure.

In consideration of these viewpoints the above evaluation made it possible to express in one equation of the form of equation (8) the explored relationships - mutual change of pressure and temperature of the aspirated air (throttling and overcharging) and the change of the spontaneous ignition and the compression. In other words, the mean temperature variation could be so expressed in a relation that a rapid temperature rise was computed at the point where the indicator card predicted the incipient detonation. Ignition-lag studies of fuels for Otto engines are available only in parts. Lindner has made some ignition-lag measurements on gasoline sprays, but his findings are inapplicable to the evaluations because in the Otto engine the fuel is practically completely vaporized at the end of compression, so that the heating processes of the fuel and the vaporization at ignition by incipient detonation are no longer apparent. The decision concerning the applicability of constants obtained from the ignition-lag measurements for detonation tests must be held in abeyance pending further experimentation with vaporized fuels. These measurements are being made once with

adiabatic compression as applied by H. T. Tizard and D. R. Pye (reference 28) and once by blowing fuel vapor into hot air.

Figures 17 and 18 show temperature curves obtained with changes in compression and initial temperature from tests at knock limitations. The application of the same formula to test series beginning in the detonation-free zone and terminating in the severe detonation zone gives the temperature curves illustrated in figure 19. (The test series of figure 19 refers to a different fuel from that of figures 17 and 18.) The temperature rise for detonating operation occurs at a crank setting where much fuel is still unburnt, for detonation-free operation the temperature rise is small shortly before terminated combustion in the unburnt part. This would turn into a rapid burning only at a later interval. The evaluation is not to be interpreted that the temperature variation in the unburnt part actually corresponds to the curves shown in the plots. They are merely intended to show that the detonation process can be explained with a reaction, the speed of which can be represented by the reciprocal value of a pressure power and an e function of the reciprocal value of the temperature without making any predictions as to the time rate of change.

On the basis of the above reasoning, it is to be expected in agreement with the customary explanation of the effect of antiknocks (references 24 and 25), that the interaction of lead will result in a check of the reaction (for instance, chain interrupting). The effect of tetra ethyl lead will probably not show as a change in the value b of the reaction formula which characterizes essentially the molecular properties, but in a changed d in a constant factor in the reaction formula. If the enhanced detonation tendency is equalized only by a change in pressure, the reaction formula undergoes a change insofar as at knock limitation the value p^n and hence p must be changed for a constant factor in correspondence with the change in d .

The evaluation included the experiments of P. Giertz with supercharge and increased air temperature at different spark advances and excess of air. This was supplemented by investigations of the knock limitations under changed pressure and temperature before the engine, as well as for changed spark advance and compression.

The test results for the detonation limit of gasoline with and without leaded fuel are given in figure 20. The detonation reducing effect was mathematically allowed for with a change in d with a constant factor, which corresponds to a proportional change of the admissible value for p . The experimental determination was in good accord with this reasoning. The solid curves represent the experimental data, the dashed curves the experimental values with leaded fuel reduced by a constant factor. The agreement is satisfactory.

The above method of evaluation produced satisfactory results in several test series on two engines. To what extent and with what limitations the investigating methods are practical remains to be proved in further engine tests.

Translation by J. Vanier,
National Advisory Committee
for Aeronautics.

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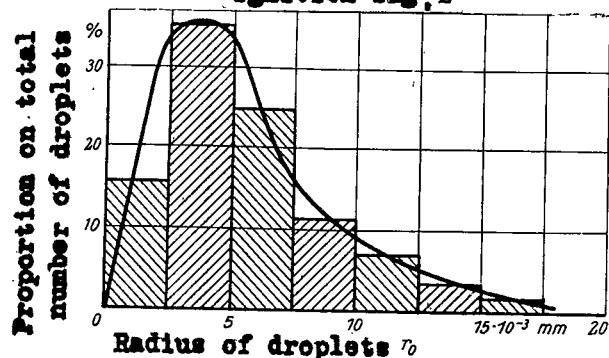
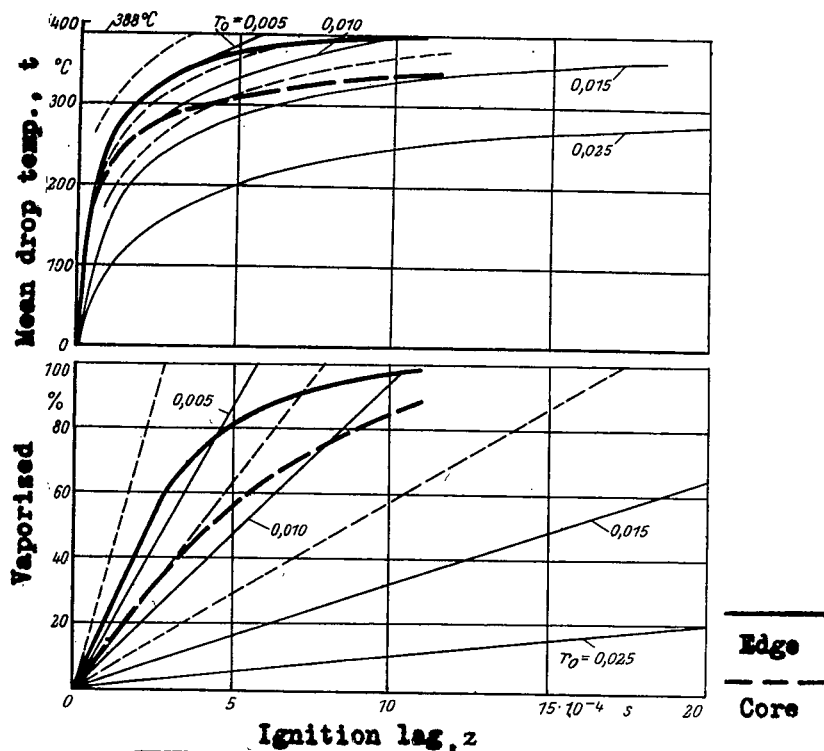


Figure 1.- Vaporization in fuel spray and at spray boundary.

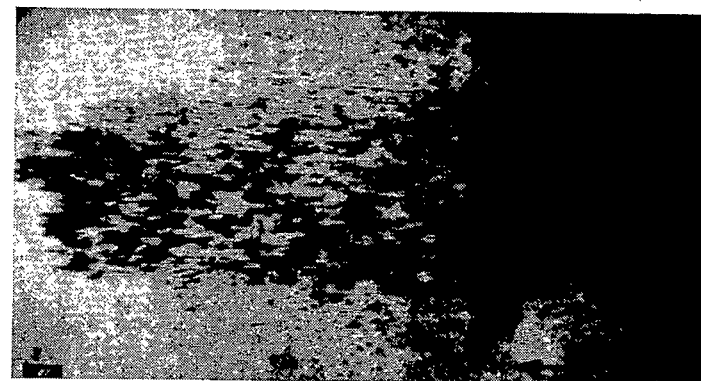


Figure 2.- View of forward portion of spray (in transmitting light 5X.)



Figure 3.- View of central portion of spray (transmitting light; 5X)

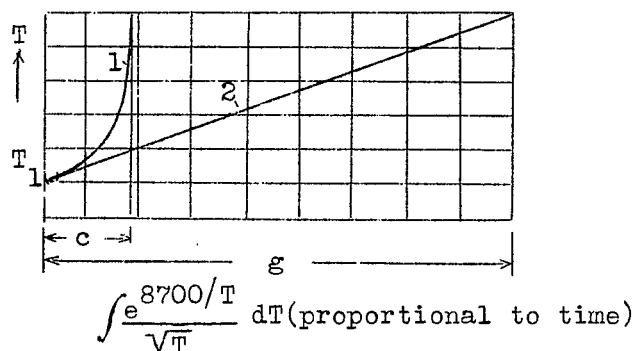


Figure 4.- Temperature rise during reaction with allowance for reaction velocity; (1) at reaction velocity equivalent to initial temperature; (2) in relation to temperature T .

T_1 = Initial temperature

$$\beta = c/g$$

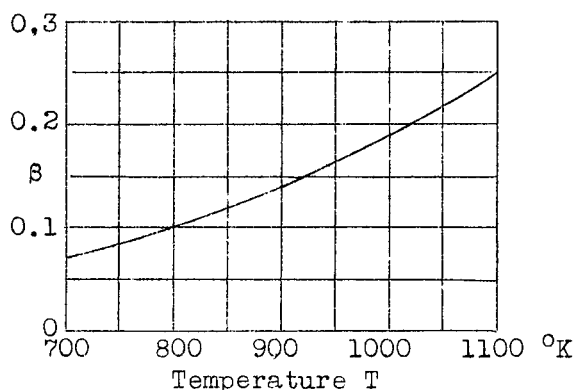


Figure 5.- Change of value β with temperature T
 $Qa/R = 8700$.

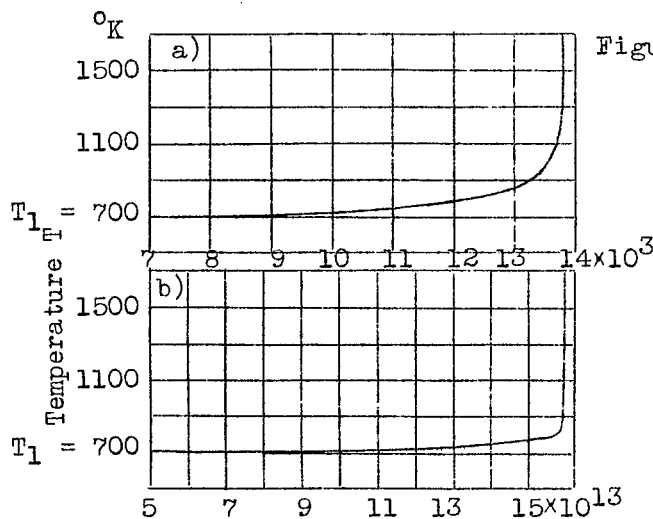


Figure 6.- Presentation of integral

$$\int_{T_1}^T \frac{e^{b/T}}{\sqrt{T}} dT \text{ between}$$

$T_1 = 700$ °K and any other temperature T (made up to 1700°K) for $b = 8700$ (top) and $b = 23,000$ (bottom).

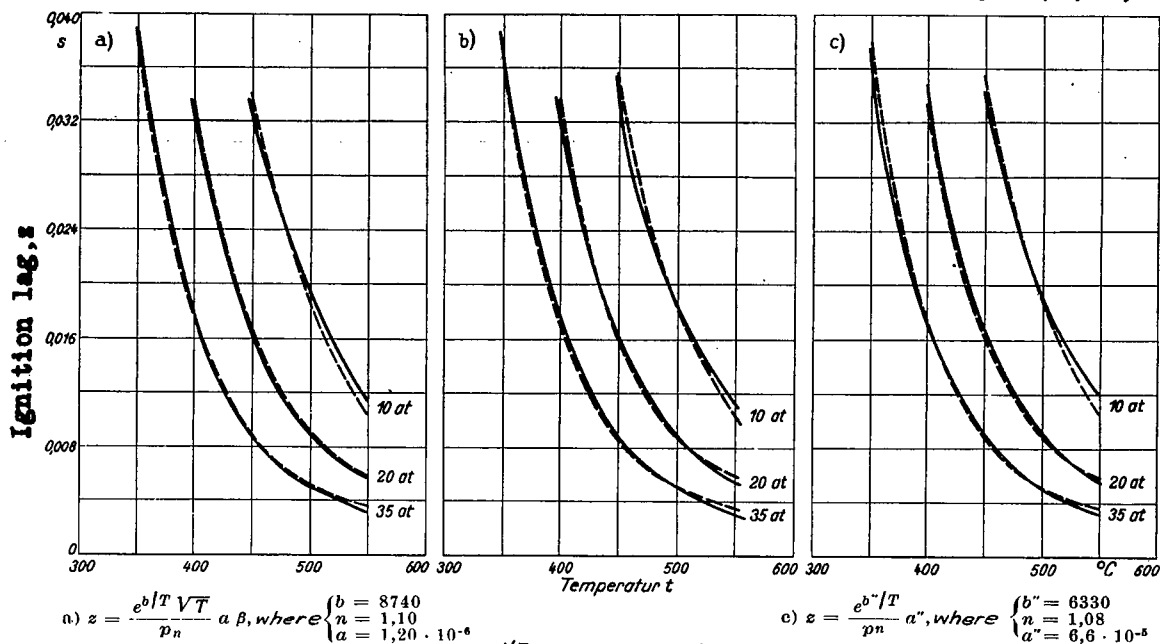


Figure 7.- Ignition lag plotted against pressure and temperature.

(The dotted curves are obtained from experiments).

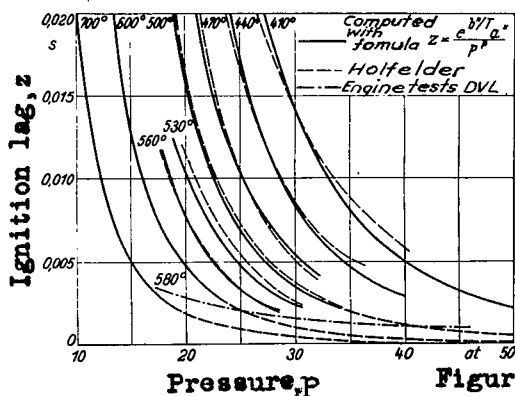


Figure 8.- Ignition lag plotted against pressure and temperature.

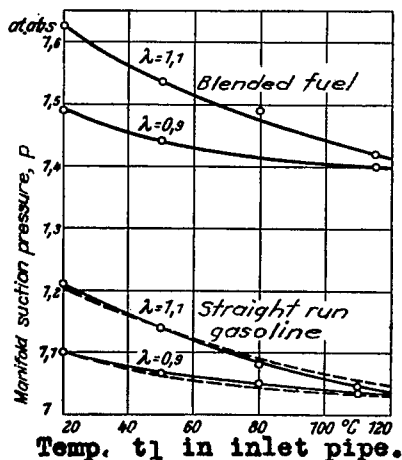
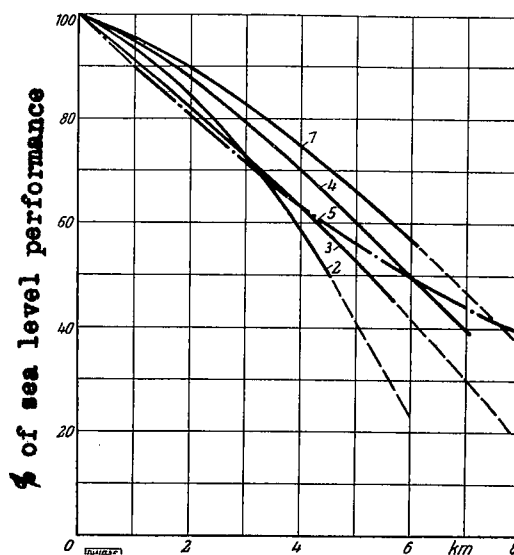


Figure 20.- Pressure in intake pipes corresponding to knock limitations at different temperatures of inducted air for plain and leaded gasoline.



- Altitude
- 1- Prechamber engine $\epsilon = 14$; 1500 r.p.m.
 - 2- Lanova " $\epsilon = 12.5$; 1490 r.p.m.
 - 3- " " $\epsilon = 15$; 1490 r.p.m.
 - 4- Direct injection $\epsilon = 12.2$

5- Otto cycle engine; $N = N_0 \frac{p}{p_0} \sqrt{\frac{T_0}{T}}$

Figure 11.- Diesel engine performance against altitude.

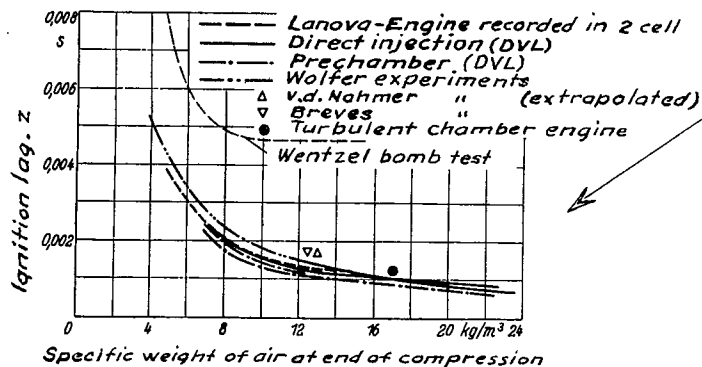


Figure 9.-- Ignition lag against specific weight of air at end of compression for different Diesel cycles and bomb tests.

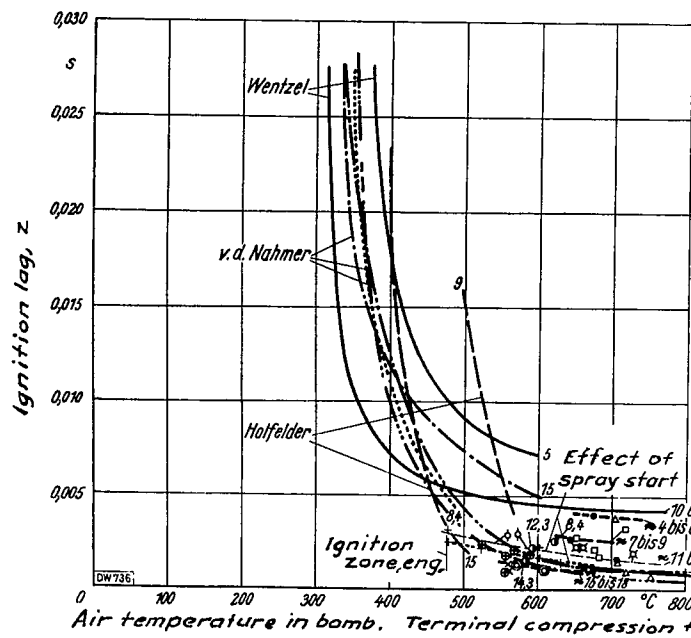


Figure 10.-- Recorded relationship between ignition lag and temperature, engine and bomb tests.

Specific weight of charge γ in kg./m^3			
Bomb test	Wentzel	5	10 to 15
	Holfelder	9	15
	v.d. Nahmer (different prechamber inserts)	13	
	"	8,4	15
	Breves	12,4	14
	DVL	4 to 6	7 " 9
	"	11 to 14	16 " 18

Engine tests

- △ Lanova method with spray timing $\epsilon = 15$
- " " without "air cell." " = 12.5
- ◇ Acro
- ◇ Direct injection
- ◇ " with after chamber
- ⊙ Turbulent chamber
- × Prechamber, supercharger
- ⊙ Rothrock and Waldron $\gamma = 12.4$ to 13.8
- Prechamber method

--- Interpolated according to test data by Wolfer ($\gamma = 13 \text{ kg/m}^3$) (tests in bomb set up simulating engine conditions)

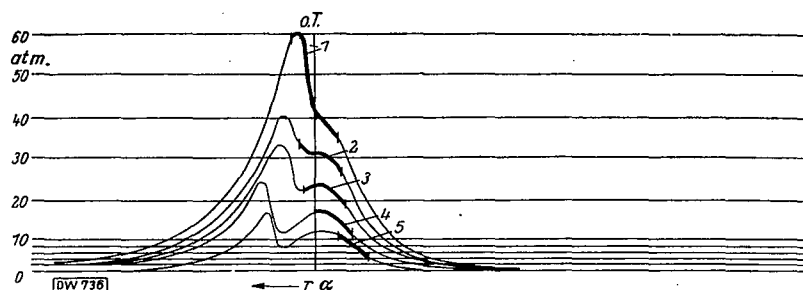


Figure 12.- Indicator cards at different induction pressures p Lanova cycle $\epsilon = 12.5$; $n = 1490$ r.p.m.

1, $p = 1.03$	at abs. equiv. to 0	m alt.	$p_e = 6.04$	at.; start of spray	13°	B.T.C.
2, $p = 0.80$	"	"	"	"	"	"
3, $p = 0.62$	"	"	"	"	"	"
4, $p = 0.54$	"	"	"	"	"	"
5, $p = 0.48$	"	"	"	"	"	"

The solid portion indicates the spray period. The height data refer to altitude of equal pressure.

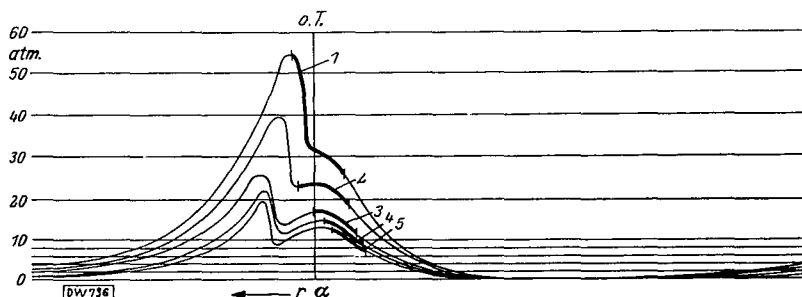


Figure 13.- Indicator cards of cylinder main chamber at different p and $\epsilon = 15$.

1, $p = 1.03$	at abs. equiv. to 0	m alt.	$p_e = 5.96$	at.; start of spray	9°	B.T.C.
2, $p = 0.81$	"	"	"	"	"	"
3, $p = 0.62$	"	"	"	"	"	"
4, $p = 0.47$	"	"	"	"	"	"
5, $p = 0.345$	"	"	"	"	"	"

The solid portion corresponds to spray period.
Height data refer to equal pressure height.

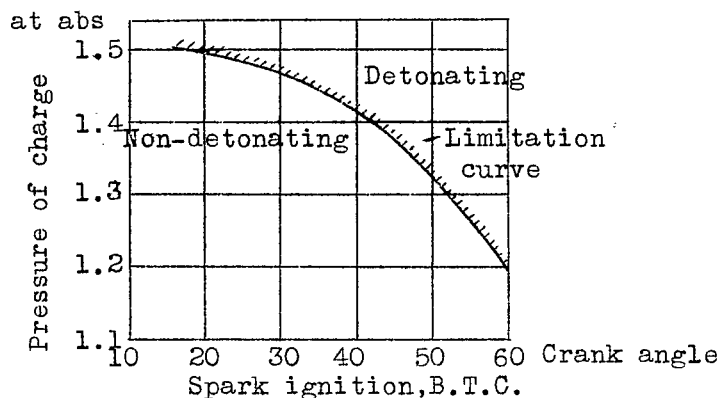


Figure 14.- Knock limitations plotted against spark ignition.

- a. p_e (OZ 87) 100°C
- b. p_l (OZ 87) 100°C
- c. p_e (OZ 73) 20°C
- d. p_e (OZ 73) 100°C
- e. p_l (OZ 73) 20°C
- f. p_l (OZ 73) 100°C

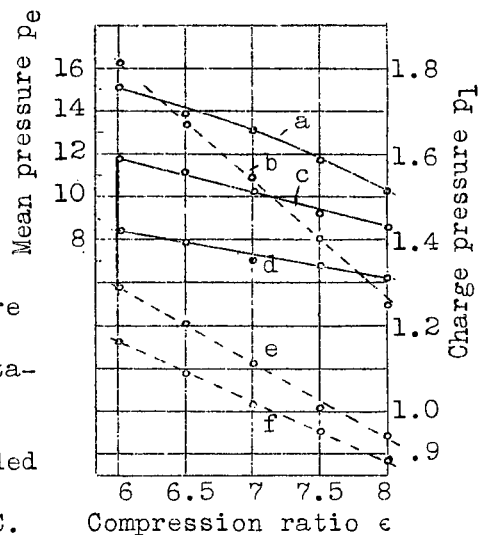


Figure 15.- Charge pressure p_l and mean pressure p_e at knock limitations against compression ratio ϵ .

OZ 73 Gasoline BO not leaded
OZ 87 " " leaded

$\lambda = 0.9$; Spark ignition 38° B.T.C.

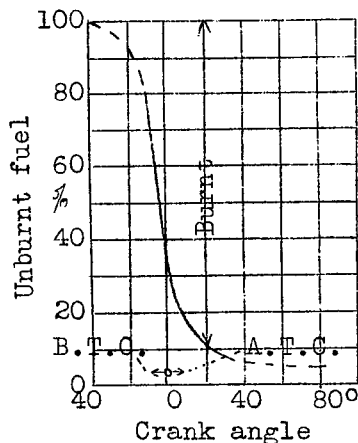


Figure 16.- Combustion versus crank setting.

Spark ignition 38° B.T.C.

$n = 2600$ r.p.m.

Figure 19.- Temperature distribution for unburned fuel quota in cylinder under conditions of Figs. 17 and 18 best for a test series starting in the detonating and terminating in the knock-free zone air temperature: 80°C , spark ignition: 38° B.T.C.

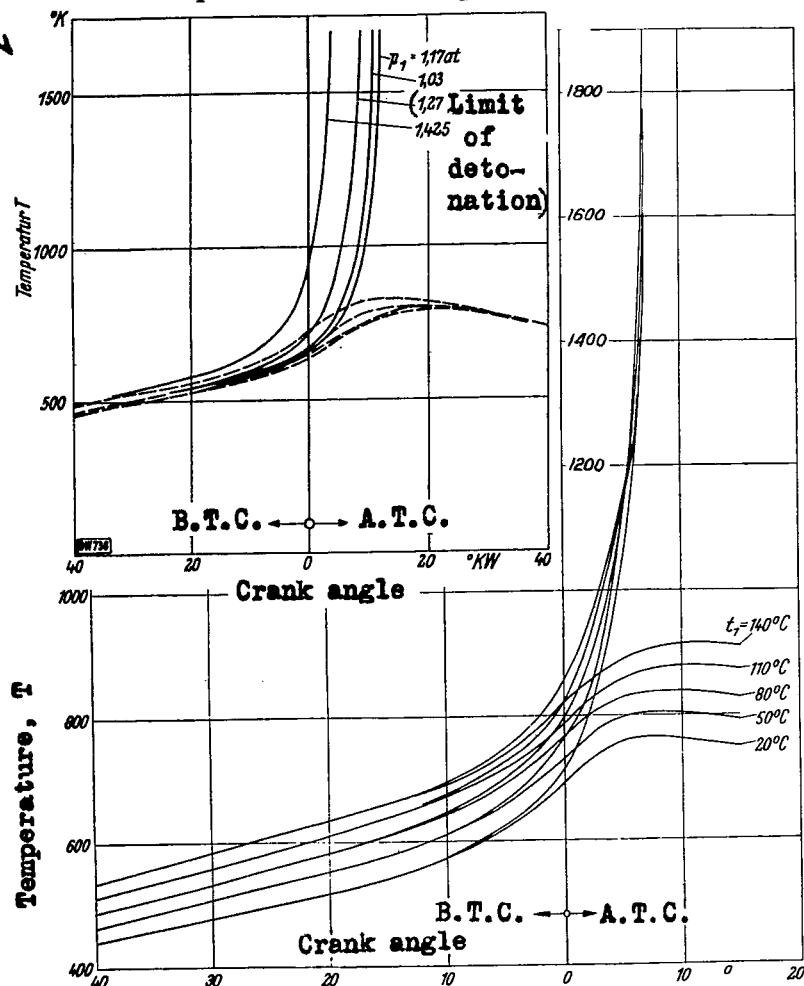


Figure 17.- Mixture temperature T versus start of ignition and initial temperature T_1 at constant compression ratio $\epsilon = 6$.

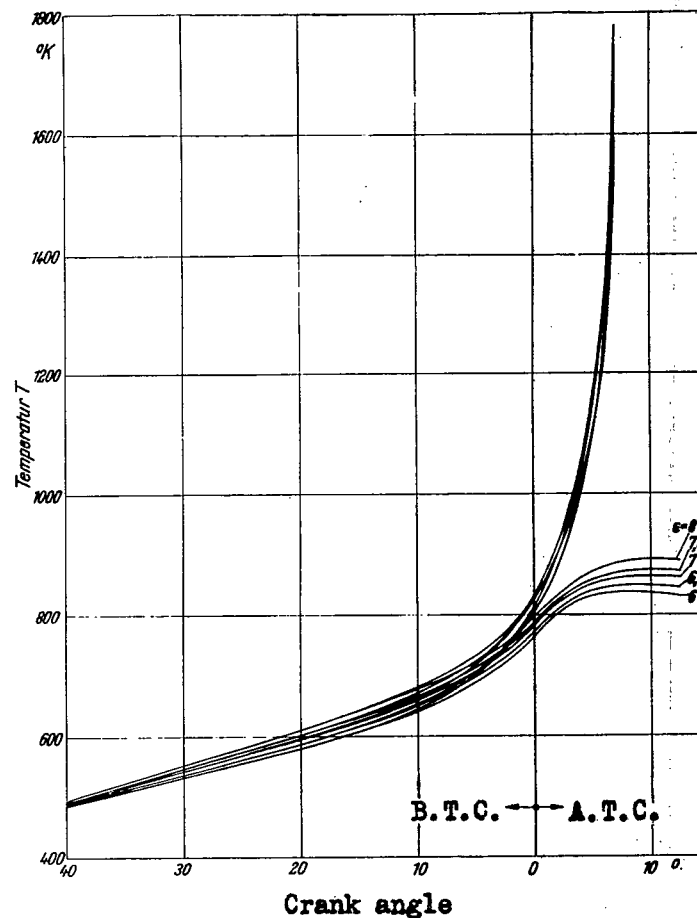


Figure 18.- Mixture temperature T versus start of ignition and compression ratio ϵ at constant initial temperature $t_1 = 80^{\circ}\text{C}$

